CHAPTER 19

BEAM INSTRUMENTATION

19.1 TT2/TT10 INSTRUMENTATION

19.1.1 Beam Position Measurement

The beam is transferred from the PS to the SPS via the combined TT2/TT10 transfer line (see Chap. 15). Each of these lines is equipped with beam position monitors (BPM) of which 6 are located in TT2 and 14 in TT10. Each BPM is mounted orthogonally and consists of four, 60 cm long, straight strip-line electrodes. The vertical and horizontal position of the beam centroid is obtained from each BPM.

The acquisition system is based on logarithmic amplifier electronics [1], where the position is obtained directly as the LOG (electrode A) – LOG (electrode B). This method has the advantage that only one coaxial cable is required to transmit the position data to the surface buildings. In order to minimise the cable lengths the system is split in two; with the acquisition system for the first ten BPM's in the PS Y-Building (Building 269) and the system for the second ten in the SPS at BA1. Each one of these acquisition chassis is auto-triggered by the first pick-up it contains.

The signal from each pick-up can be switched to supply one of two logarithmic amplifier chains, one working at 200 MHz for full LHC batches and SPS fixed-target proton beams, the other one working at 22 MHz for single bunches and SPS fixed-target heavy ion beams.

Calibration of the complete system is performed by injecting signals at 0 dB and ± 6 dB through the upstream ports of opposing strip-lines, allowing the offset and gain of the system to be determined for each set of acquisition electronics.

For a centred beam the linearity is ±100 μm over 70 dB, with a resolution of 20 μm for a batch measurement and 50 μm for a single bunch.

19.1.2 Intensity Measurements

The PS to SPS transfer lines are equipped with two identical fast beam current transformers for transfer efficiency measurements, one located at the beginning of TT2 and the other near the end of TT10 [2]. For LHC proton and ion bunches the dynamic range of the transformer covers intensities from 3×10^8 to 5×10^{11} charges per bunch, with a bandwidth covering the range from 200 Hz – 500 MHz and a very low droop of less than 0.2 % per μs. This low droop means that no baseline restitution is required during the passage of the LHC batch. The acquisition electronics is based on a 40 MHz integrator chip developed by the Laboratoire de Physique Corpusculaire (Clermont-Ferrand) for use in the LHCb Pre-shower Detector [3]. This allows bunch by bunch intensity measurements for LHC type beams. The integrated charge is digitised using a 12-bit ADC and treated and stored using the digital acquisition board (DAB) developed for the LHC beam position system (see Vol. 1, Sect. 13.1). Synchronisation of the acquisition with each bunch is obtained using the SPS beam synchronous timing as provided by the TTC system (Sect. 19.2).

Calibration of the system is performed by injecting a stable current, corresponding to 2×10^{10} charges in 25 ns, into a calibration winding around each transformer. A single shot bunch-by-bunch intensity measurement is predicted to have a resolution of ~5×10^8 charges and an accuracy of ~2×10^9 charges.

19.1.3 Beam Profile Monitors

The measurement of the beam profile at several locations in the transfer line is needed in order to determine the transverse beam size of the injected beams at each location and hence compute their emittance. Five standard SPS BTV tanks are installed along the injection line TT2/TT10. Another 12 screen monitors are also available for simple beam observation purposes in case of problems with the BPMs.

The BTV mechanisms are equipped with two different types of screen material [7]:

- Luminescent screens made of 1 mm thick chromium doped alumina (AL_2O_3 [Cr]).
- Optical Transition Radiation [OTR] screens made of a 12 μm thick foil of titanium.

The alumina screens are normally used for low intensity beams and the OTR screens for high intensity ones. The light produced by the screen is extracted through a window and focused on an image intensifier optically coupled to a standard CCD camera.

A set of neutral density optical attenuators controls the quantity of light transmitted to the camera as a means of coping with the large dynamic range to be covered. In terms of intensity the dynamic range goes from $5x10^9$ protons to around $2x10^{13}$ protons per injection.

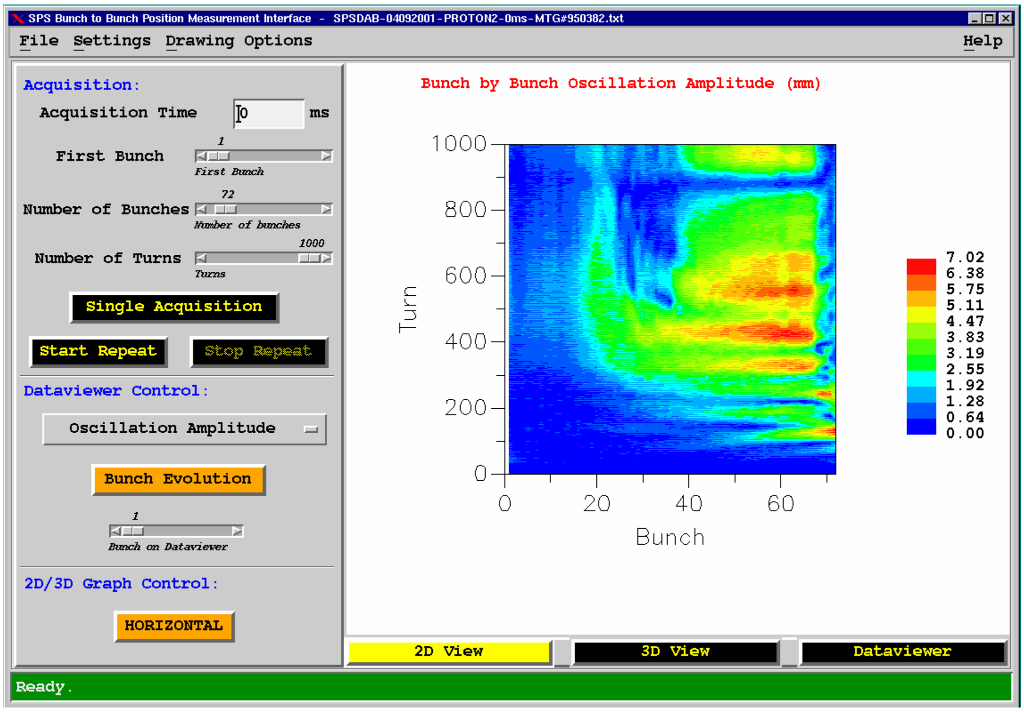
The TV signal is connected to TV monitors that allow the observation of the beam in real time in the Control Room. In addition, the signal is passed to a VME acquisition board that digitises the TV frame with a resolution of 300 x 400 pixels. The digitisation is made with 8-bit precision. The data from the acquisition is used to generate horizontal and vertical projections for a single frame that corresponds to a single pass of the beam. A 2-Dimensional surface representation is also available. Depending on the choice of the fixed optics in front of the CCD camera, the spatial resolution can range from 150 to 300 µm/pixel.

One of the TT10 screens is equipped with a 32 channel multi-anode photomultiplier making it possible to measure the profiles of the individual bunches of a PS batch at 40 MHz [9]. The multi-anode photomultiplier is mounted on a rotating table enabling the system to acquire the beam projection along the desired axis.

19.2 SPS INSTRUMENTATION

19.2.1 Beam Position Measurement

For LHC type beams the first turn and orbit are measured in the SPS using the standard SPS orbit system (MOPOS) [4]. Most of the 216 pick-ups used are electrostatic “shoebox” monitors, measuring either in the horizontal (at high β_H) or vertical (at high β_V) plane. The signals from these high impedance pick-ups are matched to 50 Ω at 200 MHz before passing through a passive hybrid to produce a sum and difference signal. The acquisition system is based around a 200 MHz homodyne receiver, the output of which is filtered, sampled and digitised to give a sum and difference signal from which the position can be calculated. Gain switching (in 10 dB steps up to 90 dB) is required to cover the large dynamic range needed for all types of SPS beams, with each gain requiring its own calibration factors. The system is equipped with enough memory to store the orbit for all turns during a given SPS elementary cycle. This enables multi-turn (normally 1000 turn) measurements to be performed with specific monitors, or for all beam position monitors, at any time within the cycle.


SPS Bunch to Bunch Position Measurement Interface - SPSDAB-04092001-PROTON2-0ms-MTG#950382.txt

Acquisition:
Acquisition Time 0 ms
First Bunch 1
Number of Bunches 72
Number of Turns 1000
Dataviewer Control: Oscillation Amplitude
Bunch on Dataviewer 1
2D/3D Graph Control: HORIZONTAL
Ready.

Figure 19.1 Study of the electron cloud instability in the SPS using the 40MHz bunch by bunch position measurement system.

Three large aperture strip-line coupler pick-ups (BPCE) form part of the SPS to LHC extraction interlock on each LHC extraction channel, in LSS4 and LSS6. The acquisition of these pick-ups is performed using the standard MOPOS system, with an additional algorithm incorporated to correct for the non-linearity of the pick-up at large amplitudes. These pick-ups are read out 50 ms before the extraction and are used to ensure that the extraction bump is within the limits set for the acceptance of the septum magnet.

In addition to the global orbit acquisition, the SPS is equipped with a single BPM located in LSS4. This BPM is fitted with LEP-type button electrodes and the LHC orbit acquisition electronics. This allows the measurement of bunch by bunch position over thousands of turns at any time in the cycle for any beam spaced by multiples of 25 ns. Such a pick-up has proved very useful for instability studies and in particular to understand the behavior of the LHC batch or batches under the influence of an electron cloud. Fig. 19.1 shows a typical result from such a study for a 72 bunch LHC batch at injection in the SPS. The first bunches are seen to be stable, while bunches towards the tail of the batch develop large oscillation amplitudes as a result of instabilities provoked by the electron cloud.

19.2.2 Beam Loss Monitors

The SPS beam-loss monitoring (BLM) system is used to localise beam losses during the injection, acceleration and extraction processes. Nearly 300 ionisation chambers are installed around the SPS ring. The currents generated by the chambers are treated by the BLM acquisition system which consists of 10 VME chassis which are installed in various surface buildings around the machine.

The ionisation chambers are parallel plate type monitors filled with nitrogen at atmospheric pressure. Each monitor has a volume of one liter. The electrical drift field strength is set to 1600 V/cm. An integrator integrates the ionisation chamber current during the whole SPS elementary cycle. Every 20 ms, a 12 bit ADC samples the integrator output and the digital value is stored in the memory of a VME acquisition module.

The acquisitions are triggered using SPS timing events pre-programmed in the SPS elementary cycle. The beam-loss server returns data either in raw ADC counts, or calibrated in units of mGy. A fixed-display is provided for the machine operators. This display can show the integral dose of each Beam Loss monitor or the evolution of losses for a single Beam Loss monitor throughout an elementary cycle.

The dynamic range of the LHC beams, from pilot to four batches at nominal intensity is around 10^4. Assuming that the losses scale linearly with the total intensity, several gain stages are needed on the acquisition board to cover this large dynamic range with a 12 bit ADC.

A signal to the beam dump is generated when the loss rate exceeds a given preset threshold [8].

19.2.3 Intensity Measurement

The SPS is equipped three DC beam current transformers (BCT). Two are for high intensity beams and one for low intensities. The low intensity BCT, located in Point 4 (BCT414), covers the range from 2 μA to 50 mA. This corresponds to the range 3×10^8 charges up to 7×10^{12} charges in 23 μs. This BCT it therefore used for measuring single bunches and the heavy ion fixed-target beam. Two identical high intensity BCTs are located in Point 1 (BCT116) and Point 3 (BCT318). The measuring range of these BCTs is between 20 μA and 1100 mA. The corresponding beam intensities are 3×10^9 charges and 1.6×10^{14} charges in 23 μs. Two such BCTs are provided for redundancy reasons as the signals are also used by the beam dump system for its energy tracking. A direct analogue output from each of the three BCTs is sent to the accelerator control room for use on the teletext server showing the SPS status pages.

Point 3 in the SPS is also equipped with a fast beam current transformer identical to those installed in TT2 and TT10 (see Sect. 19.1). For LHC type beams this monitor is capable of bunch-by-bunch measurements at rates of up to 100 Hz throughout the SPS cycle. The measurements are triggered by the SPS beam synchronous timing. Such measurements allow the visualisation of bunch-by-bunch intensity variations at injection and extraction, but also give the relative loss from each bunch throughout the acceleration process.

Passive beam current transformers are also installed in points 4 and 6 and provide analogue signals which are used to time-in the extraction systems of TI8 and TI2 respectively.

19.2.4 Tune and Chromaticity Measurement

The dedicated SPS tune measurement system uses a single kick technique followed by FFT analysis to determine the horizontal and vertical betatron tunes of the machine. Each plane is equipped with four "Q-kicker" modules of varying strength, allowing kicks of up to 2 mm at 450 GeV. It is also possible to apply a chirp excitation to the beam via the transverse damper, with which it is possible to follow the tune evolution along the cycle in 50 ms intervals. Chromaticity is measured by changing the RF frequency on successive cycles and measuring the corresponding tune change. The beam oscillation information is retrieved from both strip-line couplers and electrostatic pick-ups, depending on the mode of operation.

The tune acquisition system consists of a CPU module (PowerPC based), a main timing receiver module (TG8), a timing module providing ADC sampling clocks and up to 12 Beam Oscillation System sampler modules (BOSC) [5]. Each of the BOSC modules can be used to acquire two individual signals with 16 bit ADCs over up to 10^6 consecutive SPS turns. Typically the two signals are the delta and sum signals from a specific beam position pickup. Three different beam types can be treated:

1. A single bunch. As the module used to generate the ADC sampling clock has a jitter of more than 10 nsec, an auto-trigger (a peak and hold mechanism that finds the peak of the sum signal) is used to sample the data for sum and delta channels.
2. Low intensity batched beams, typically heavy ions. The input signals are filtered at 4 times the revolution frequency and sampled using the standard sample and hold mode. Specially designed low-noise amplifiers allow a correct acquisition even if the total intensity is down to a few 10^9 charges.
3. High intensity batched beams. Here the front-end electronics is based on high frequency FET amplifiers inside the SPS tunnel that have the advantage of not needing a 200 MHz structure to work. This system can therefore also be used when setting-up the SPS resonant slow extraction.

The first two modes above can cover a dynamic range of 10^3 or 60 dB using external gain stages. The low-level software is completely driven by the MTG timing events. The generic warning event which arrives 500 msec before the beam is injected is used to program the gains and delays needed for the next cycle. The generic beam-in event, which arrives at turn zero of the injected beam, is used to reset the ADC samplers and to start the acquisition from that turn onwards. The generic beam-out event, which arrives at the end of the elementary cycle, is used for book-keeping on the completed cycle and to trigger the reading of raw-data from the low-level crate.

19.2.5 Head-Tail Monitor

The head-tail monitor was originally installed to study a new technique for the measurement of the chromaticity, via head-tail phase shifts [6]. It has now also become a standard instrument for providing transverse, bunch-by-bunch, wide band signals. These are used to study a variety of instability issues in particular for LHC type beams. The system consists of a 60 cm long strip-line coupler, followed by a 2 MHz- 2 GHz passive hybrid and a fast digital sampling oscilloscope (2 Giga-samples/s). The acquisition is gated around a region of interest, which may be a single bunch, a full batch or a complete turn and is re-triggered on this region for up to 350 consecutive turns. The resulting data is retrieved via a GPIB link for analysis and display by a high level graphical user interface.

19.2.6 Beam Synchronous Timing

The beam synchronous timing (BST) is required for much of the specific LHC beam instrumentation in the SPS. This is distributed via a fibre-optic network, using the Timing, Trigger and Control (TTC) system designed for the LHC detectors. The TTC infrastructure allows the 40 MHz bunch clock, a 23 μs turn clock and arbitrary control data to be recuperated at each beam instrumentation station by a BST receiver card. A full description of the receiver card is given in Vol. 1 Sect. 13.9.

19.2.7 Beam Profiles Measurement Instruments

Wire Scanners

Wire scanners are the main instruments for the transverse beam emittance determination in the SPS. Two different scanner types are distinguished by the wire transport mechanisms used. The linear transportation mechanisms reach a speed of 1 m/s and are therefore limited to a maximum proton intensity of 5×10^{12}. The rotational wire mechanism based scanners reach a speed of 6 m/s and the beam heating limit is well above the nominal LHC proton intensity of 3×10^{13}. In either case the accuracy of the profile measurement is limited by the systematic errors. The lowest relative systematic error (below $\Delta\sigma/\sigma = 2\%$) is reached by the linear wire transportation system. Because of the more fragile and indirect wire position measurement system, the rotational wire scanners reach a relative systematic error of $\Delta\sigma/\sigma = 6\%$ [10]. The errors are estimated by comparing the different systems with each other under various operational conditions. In the SPS, a total of 6 linear and 6 rotational based wire systems are installed.

In the operation periods of 2002 and 2003 it was noted that the scanner tank, acting as a cavity, stored RF power which strongly heated the wires. This led to an acceptable combination of bunch length and intensity limit. If exceeded the heating often resulted in destruction of the wire. This limitation has been eliminated by introducing RF power absorber material on the inner walls of the scanner tanks. The build up of electromagnetic fields is reduced by two orders of magnitudes for some modes as seen in Figure 19.2.

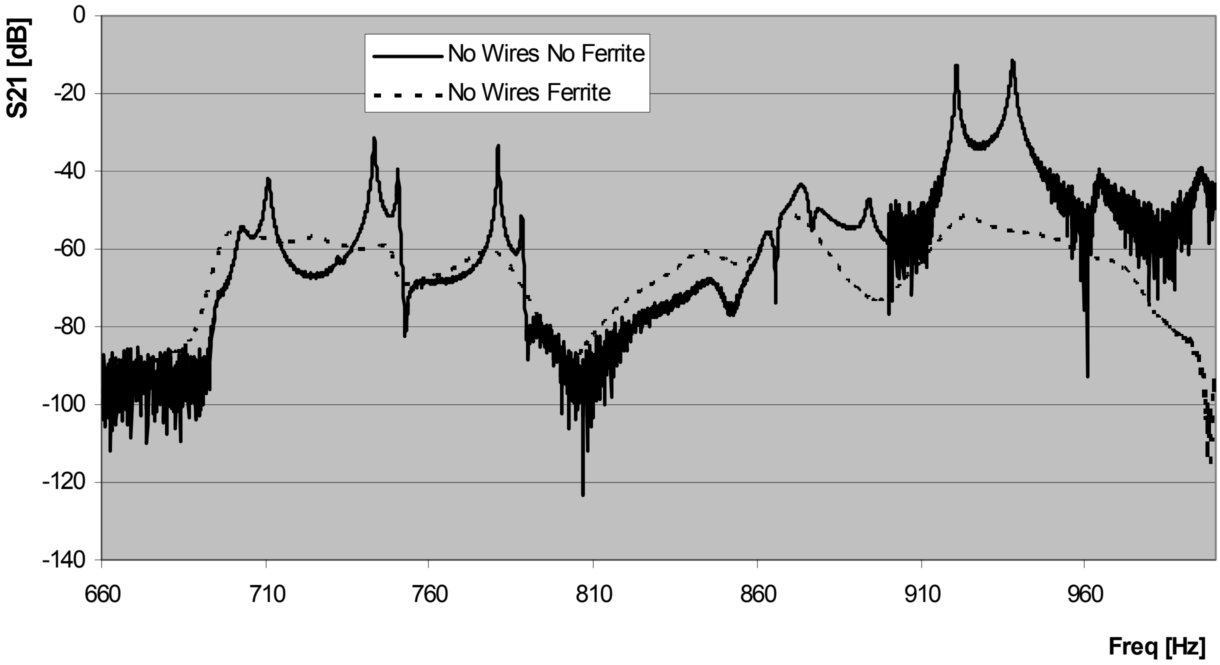


Figure 19.2: Electrical field strength spectrum inside a SPS rotational wire scanner tank with and without damping material on the walls of the tank.

Synchrotron Light Monitor

A synchrotron light monitor from the $p\bar{p}$ era [16] has been rejuvenated and installed in LSS5. It has given interesting results above 320 GeV. More work will be done to make the monitor useful at lower energies and to approach the accuracy of the LEP monitors which have provided emittance values with a precision better than 5% under comparable conditions [17].

Gas Monitors

Ionisation Profile Monitors [IPM] exploit the signal provided by the ionisation of the vacuum rest gas during the beam passage. Monitors are presently installed in LSS44 and LSS5 of the SPS. A first monitor was provided by DESY and inserted in the increased gap of a correction dipole magnet. This was done with a view to improve the resolution by chanelling the primary electrons along magnetic field lines. After acceleration of the primary electrons onto a Multi Channel Plate (MCP) for multiplication, the electrons impinge on a fast phosphor screen; the image of which is acquired by a CCD camera. This experimental monitor was installed in sector 4 of the SPS and provided good results. In particular, it gave the possibility to acquire transverse profiles with rms values below 700 µm with a good resolution (better than 50 µm) and to use the monitor in a turn by turn mode. This mode was particularly useful to perform injection matching studies [11,12].

Based on the results from the experimental monitor, a new prototype was built and installed in LSS5 of the SPS during 2002. With a more compact design the monitor is built such that it meets the criteria for incorporation into the LHC itself [13].

During the commissioning of the monitor it was discovered that electron cloud effects in the chambers of the monitor perturbed the measurements. To reduce this the various detector components located inside the SPS vacuum chamber were coated with NEG. The NEG coating is known to reduce electron multi-pacting by a reduction in the secondary electron yield of the vacuum chamber surface. The result was very good and tests resumed in 2003 with this prototype. Profiles of beams ranging from an LHC pilot bunch (5×10^9 protons) up to 4 PS batches of nominal bunches (3.5×10^{13} protons) could be measured and tracked throughout complete SPS acceleration cycles. Fig. 19.3 shows some profiles measured with this instrument. The profile of a pilot bunch accelerated to 450 GeV, measured under normal SPS vacuum pressure (2×10^{-8} hPa) is presented.

These results qualify ionisation monitors for transverse profile measurements in the SPS and in the LHC; at least for beam sizes larger than 700 µm. These instruments can also be used in turn by turn mode for injection studies.

Cross-calibrations carried out between wire scanners and the Ionisation Profile Monitors lead normally to an agreement of 3% to 5% [14]. However, for LHC type beams, the necessary dynamic range in the SPS, from one batch at 26 GeV to 4 batches at 450 GeV, cannot be covered properly with a single gain setting of the IPM. Saturation effects can generate discrepancies between the two devices of up to 20% on the measured beam rms values [12]. To solve this problem the implementation on the IPM of a variable gain control during the cycle is under study.

Gas monitors based on the luminescence of N_2 were also tested in the SPS [15]. In order to get enough signal from gas luminescence, the N_2 pressure needs to be increased locally up to 5×10^{-7} hPa. This possibility has been incorporated into the previously mentioned IPM prototype [13]. Hence, if the local N_2 pressure is increased, while transverse profiles in the vertical plane are measured by extracting the signal from ionisation, another independent optics channel provides simultaneously the profiles in the horizontal plane by looking at the signal from luminescence. Promising results were obtained in 2003 and are illustrated in Fig. 19.3.

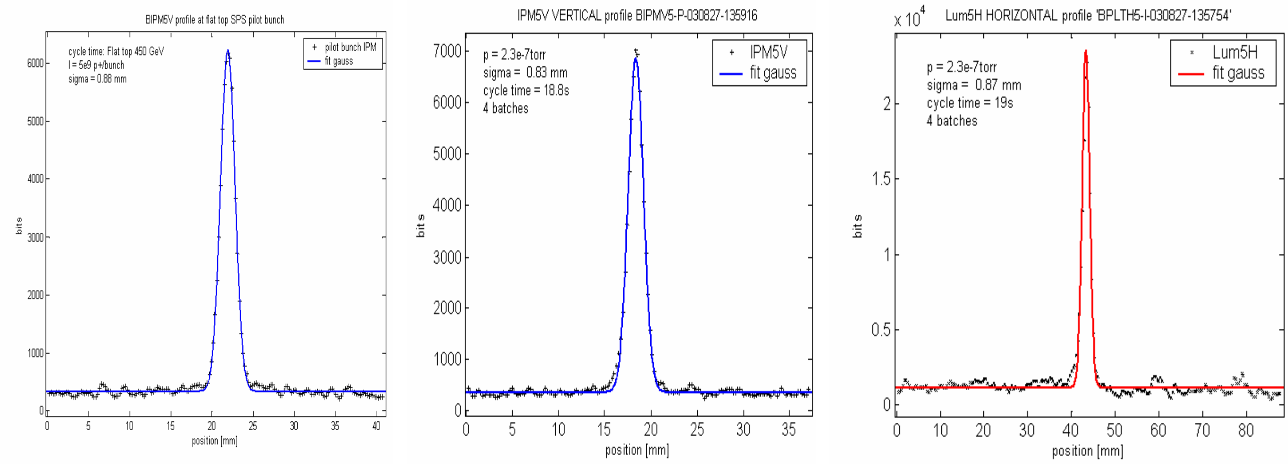


Figure 19.3: Profile measured with the SPS Gas Monitor Prototype installed in sector 5: Vertical profile (ionisation signal) of a pilot bunch (5×10^9 p) at 450 GeV, P = 2×10^{-8} hPa (left); Vertical profile (ionisation signal) of an LHC beam (3.5×10^{13} p) at 450 GeV, P = 2×10^{-7} hPa (centre); Corresponding horizontal profile (luminescence signal) of the same LHC beam as in centre (right).

19.2.8 Injection Matching Monitoring

Matching the transfer line to the machine is vital to preserve the emittance of the beam transmitted to the LHC. A new type of monitor [18] has been tested to perform the betatron and dispersion matching at injection. It is based on the measurement of the beam profile variations over a limited number of turns immediately after injection. The monitor uses a 12 µm titanium screen generating optical transition radiation (OTR) which is observed using a CCD camera operating in a dedicated fast acquisition mode. In order to avoid damaging the screen the beam is dumped after the desired number of turns. This method only requires the knowledge of the non-integer part of the tune, which can be measured very precisely with the Q-meter, or even with the matching monitor itself.

The matching monitor can provide a measurement of the mismatch to better than 1% in each plane. Two monitors are installed in the SPS: one in LSS4 in a low Dispersion region, the other in LSS5 in a region with Dispersion. Preliminary tests have been performed and were encouraging [19], see Fig. 19.4.

Another possibility for transfer line matching is to use the IPM monitor (Sect. 19.2.7) in a turn by turn mode at injection. Preliminary tests have been made and the results look encouraging [12]. The IPM monitor is, a priori, less sensitive than the screen monitor. However, it has the advantage of being non-destructive and non-intercepting and can be used to provide permanent monitoring. If the sensitivity argument turns out to be an important issue, it can be used to measure relative changes between screen re-matching procedures.

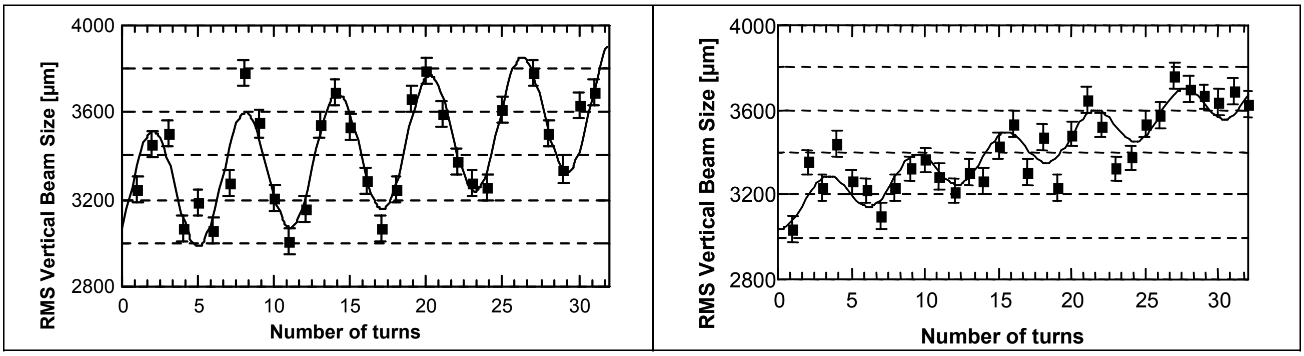


Figure 19.4: Beam size evolutions measured with the LSS4 screen monitor before and after matching [19]

19.2.9 Scrapers

The SPS beam emittance must be controlled just before extraction to the LHC. In particular, low density tails, if present, must be removed using fast scraping targets. Horizontal and vertical scrapers, originally installed in the ISR, are installed in sector 5 of the SPS to test this concept. The scrapers are associated with two sets of four collimator blocks, two horizontal and two vertical ones, which originate from LEP. The primary set is at a phase advance of 90° with respect to the scraper and the secondary set is at a phase advance of 90° with respect to the primaries. This scheme was implemented to make sure that losses induced by the scraping process can be concentrated at the scraping location, hence keeping the rest of the machine clean. This has been confirmed by tests performed at 26 GeV and 450 GeV [20]. In Fig. 19.5, it is clearly shown that during scraping the loss pattern around the SPS is not changed outside the scraper and collimator area, demonstrating the efficiency of the collimation scheme. The 3 loss peaks generated by the scraper, primary and secondary collimators are discernible when scraping.

Recent studies for protection of the LHC during the injection process have revealed the need for skew scraping in the SPS. A third scraper will therefore be installed with the other two. The exact physical angle of this scraper will be determined once the final location is known. The present location for the scraper is not optimum since the dispersion is non zero. The scraping is therefore not purely transverse, some momentum scraping also occurs. A new set of locations for the complete scraper system are presently under study. The new location for the fast scraper itself needs to have a low dispersion and space at 90° and 180° downstream for the collimator sets. Ideally the new location should not be in a clean region of the machine, since the regular use of the scraper for the LHC beams will generate significant local radiation during heavy scraping.

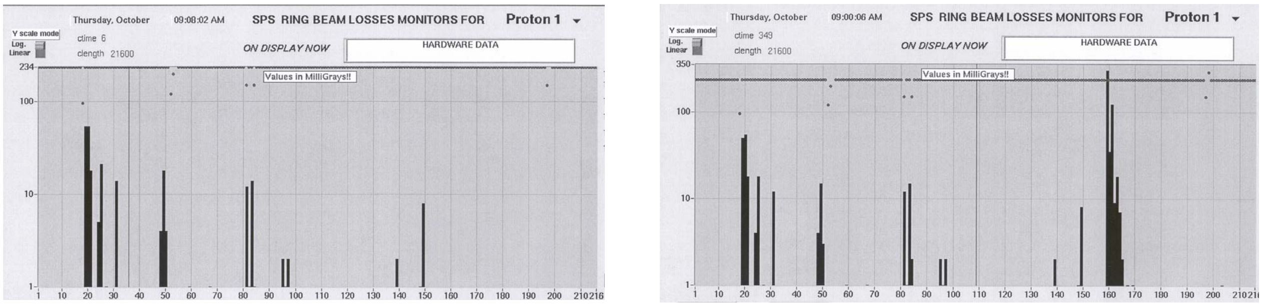


Figure 19.5: Beam losses with (left) and without (right) scraping in LSS5. Outside the scraper region there is nearly no change in the loss pattern around the ring.

19.3 EXTRACTIONS

19.3.1 BTVEs

Six new TV screens will be installed in the two fast SPS extractions, LSS4 and LSS6, in order to visualise the transverse beam spot. Two monitors are located upstream and downstream the MSE septum in LSS4 and four monitors at the entrance and exit of both the MST and the MSE septa in LSS6.

Because of the severe space constraints at these locations, TV monitors with a special geometry had to be developed and incorporated into the septum vacuum pumping modules. Each monitor is equipped with a phosphorescent alumina plate for use at low intensity and with a 12 µm titanium foil providing optical transition radiation at nominal currents. Both are approximately 20×60 mm rectangular screens, tilted by 45 degrees with respect to the beam axis and moved IN and OUT via a linear displacement controlled by stepping motors. The signal processing is the same as for the TV screens of the injection line, TT10 (Sect 19.1). The first two monitors, installed in LSS4, were successfully tested during the September 2003 test of this fast extraction.

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